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Research Paper

Georisks in railway systems under climate uncertainties by different types of sleeper/crosstie materials

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ABSTRACT

Railways have been a critical catalyst for economic and social growth around the world. They have been built using local materials to effectively suit whole-life design, construction and maintenance. The choice of construction materials often affects the life cycle performance and plays a key role in resilience of rail assets and infrastructure in an uncertain setting derived from geotechnical risks, operational changes, natural hazards and climate change effects. Nowadays, in railway industry, various materials are being installed in railway tracks as supporting structure. Railway sleepers or ties are an important element, which redistributes wheel load onto track foundation and importantly secures rail gauge. Among them is manufactured by steel, timber, polymer, composite and concrete. The choice of these sleeper materials is mainly arisen from local suitability and compatibility in a specific railway network. This research is the world first to investigate the georisks and potential consequences on track capacity and performance of railway systems under climate uncertainties. Risk analysis and ranking has been conducted using rigorous evidences from critical literature review and expert interviews. This paper highlights track failure modes, short-term and long-term stability, and ground-borne vibration, which causes excessive maintenance and service downtime. The insight into the influence of sleeper material choice will help saving life cycle costs and reducing carbon footprint from repetitive track reconstruction activities.

1. Journal aims and scopes

Railways are a key transportation system to many countries around the world. Maintaining the design geometry over their operational life and continuous services, with minimal interruptions to maintenance is a challenge to railway industry who extremely needs to guarantee safety and economic efficiency (Kreso et al., 2016; Kaewunruen and Remennikov, 2016; Dindar et al., 2016; Francis and Whitworth, 2016; Osman et al., 2017). Throughout the world, a railway track supported by ballast is widely accepted for conventional railway lines due to its advantages as inexpensive implementation costs and ease in maintenance (Remennikov and Kaewunruen, 2008; Indraratna et al., 2011; Le Pen, 2008). Ballasted railroad track infrastructure is a layered system essentially comprised of two main parts: superstructure and substructure as shown in Figure 1. The superstructure includes the main load-supporting elements of the track; it is basically constituted of rails,

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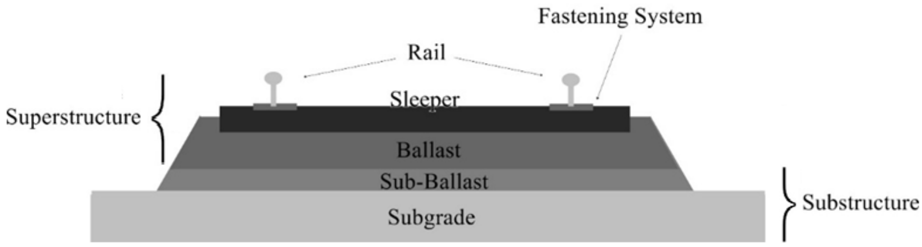

Fig. 1. Schematic illustration of a typical ballasted railway track

the fastening systems, sleepers (or crossties), under sleeper pads and ballast. The substructure is related with the geotechnical system comprising the ballast mat, sub-ballast and subgrade or formation (Esveld, 2001). The interaction between the components once they experience the loads imposed by the passage of trains is what determines the successful, reliable and safe operation of ballasted railway tracks (Kaewunruen and Remennikov, 2008; 2009).

Sleepers perform crucial roles in railway track system. Their major function is to transfer and distribute the loads applied on the rail seat to the ballast, sub-ballast and subgrade layers on an appropriate pressure level (Tavares and Kaewunruen, 2016; Tuler and Kaewunruen, 2017). Additionally, sleepers are responsible for assuring lateral resistance to the rails and stability of gauge width between the rails (Esveld, 2001). They also should attenuate vibrations caused by the passage of trains, acting as an intermediary elastic layer between rails and the ballast bed. This interface of interaction between sleepers and the ballast bed is determinant both for the superstructure as for the substructure behaviour and stability. The ballast condition under the sleeper influences the bending moments to which the sleepers are experienced as well as the load transfer path, once they are dependent on the contact area between sleeper and ballast particles (Abadi et al., 2015; Sadeghi and Barati, 2010). Moreover, sleeper's characteristics as size, dimensions, shape, weight and material also affect this contact area exerting influence mainly in the track lateral resistance, but also on pressure distribution (Sadeghi and Barati, 2010).

Research directed to the understanding of the geotechnical behaviour of railway lines still represents a small part of all effort made to improve the knowledge of the railway track system (Le Pen, 2008; Manandhar et al., 2016). A smaller number are the work that relates the sleepers to the geotechnical behaviour, especially those that emphasize the type of sleeper employed. Based on rigorous search and review of open literature, the georisk profiling and evaluation for railway systems under climate uncertainties considering different types of sleepers or crossties materials have not been conducted. It is clear that risk profiling and analysis considering train-track interaction with various sleeper materials in accordance with ISO 31000 is relatively new. Most previous work has been based on slope stability and geological conditions without considering track components, track stability and real operational parameters, which cause various issues of train-track interaction (Makino, et al., 2015; Sowmiya et wl., 2015; Giang et al., 2016). This present paper thus aims to elaborate overall systems risk analysis considering each principal sleeper type using evidences from critical literature review and expert interviews. The paper highlight risk analysis and prioritisation considering train-track behaviour and how the interaction is reflected in terms of particular geotechnical risks in railway track systems exposed to climate uncertainties.

2. Types of railway sleepers/crossties

Since the beginning of the history of railways, timber is the main and most used material for sleepers. Due to a scarcity of noble wood, the high price and increased maintenance requirements, the need for other materials has raised (Xiao et al., 2014). Concrete and steel have emerged as options to new lines. Mechanical advantages and lower susceptibility to wear are the major appealing features presented by steel and concrete sleepers. However, they do not have mechanical properties compatible with the timber sleeper, making ineffective the replacement and co-operation. Therefore new timber sleepers still are a more favourable option in a short term to replace the damaged sleepers in existing lines (Van Erp and McKay, 2013). More recently, environmental concerns and the search for an alternative able to reproduce behaviour more comparable to timber have increased the research on plastic/polymer and fibre composite sleepers (Van Erp and McKay, 2013).

2.1 Timber

A major advantage of timber sleepers is their flexibility, which results in a great ability to resist vibrations deriving from dynamic loads in railway track system (Bastos, 1999; Kaewunruen, 2014). The ease of handling, replacement, and adaptation to track systems are other benefits of this material. Accordantly to Manalo (2011), timber sleepers can be suited to all types of railway track. Additionally, the electrical isolation provided by timber sleeper is valuable to the signalling system and only plastic or fibre composites sleepers could also match this characteristic. Esveld (2001) arranged timber sleepers into two categories: softwood (e.g. pinewood) and hardwood (e.g. beech, oak, tropical tree). Hardwood timber is the most common sleeper material in railway lines in the world. Its advantages over the softwood timber are its greatest strength and durability. However, over the years the hardwood timber has become increasingly expensive, its availability is reducing and which is still available no longer has the same quality (Manalo, 2011).

Although more resistant to fungal decay, softwood sleepers offer less resistance to end splitting, gauge spreading, and spike hole enlargement than hardwood sleepers. Furthermore, they are less effective in transmitting loads to the ballast section as hardwood sleepers. Due to this difference in loads transmission hardwood sleepers and softwood sleepers should not be used together on the railway track (Wolf et al., 2014). Due to diverse environmental conditions, woods are susceptible to severe degradation due to the attack of various organisms. The resistance of untreated wood to fungal decay in service above ground is low, affecting its durability. Non-durable timbers generally require preservative treatment if they are to be used in exposed conditions, adding significantly to their cost. Moreover, there is growing concern regarding the use and disposal of this impregnated material their consequences for the environment (Xiao et al., 2014).

2.2 Concrete

After the Second World War, the use of concrete sleepers had a significant increase in Britain and Europe due to the timber scarcity. Progressively, reinforced and pre-stressed concrete sleepers have replaced timber and steel sleepers (Sadeghi and Barati, 2010) due to their prolonged life cycle and reduced maintenance costs (Setsobhonkul et al., 2017). Two varieties of concrete sleepers are offered in the market accordingly to Esveld (2001): reinforced twin-block and prestressed monoblock sleepers. The twin-block consists of two blocks of reinforced concrete connected by a steel bar or stiff steel beam, while monoblock sleepers consist of one prestressing reinforced concrete beam (Li, 2012). Monoblock concrete sleeper is the type that has greater acceptance in the market due to its superior durability in the face of unfavourable environments (You et al., 2017). Another advantage observed is the resistance to twist, failure commonly presented by twin block concrete sleepers. Because of this usual failure the installing process of this type of sleeper requires greater care, making it more difficult to handle and contributing to a lower acceptance, even with their reduced weight compared to monoblock sleepers. Concrete is known for its high resistance to compression, on the other hand, presents weakness when it comes to tension. Due to this characteristic, monoblock concrete sleepers use the technique of prestressing to withstand the dynamic loads arising from the passage of the train. This procedure consists of the tensioning of steel rods before or after the concrete is moulded. Prestressed concrete presents increased ductility, higher flexural strength and resistance to cracking (Wolf et al., 2014; You et al., 2017). The stability and slight position movement offered by prestressed concrete sleepers because of its heavy weight meant that it had a significant acceptance in high-speed lines. At the same time, the great weight reduces mobility, making it difficult to transport and being necessary specific equipment for installation which increases the costs of concrete sleepers. One of the causes of this high weight is a need for greater thicknesses in comparison to timber sleepers with the aim of reducing dynamic tension at the bottom fibre (Li and Selig, 1995).

Costs for producing and maintaining prestressed concrete sleepers are considerably elevated. Their initial costs are about twice that the hardwood timber sleepers (Kaewunruen, 2014). However, due to its high durability and specifications that comply with the solicitations of a railway system, prestressed concrete sleepers can be currently considered as the best cost-benefit option to serve ballasted railway lines (Li and Selig, 1995) and the most preferred sleeper to railway tracks nowadays.

2.3 Steel

With a typical lifecycle of about 20-30 years, steel sleepers emerged as a first option to substitute timber sleepers around the 1880s. A steel sleeper presents higher mechanical strength, can be lighter than timber and is easy to handle, they can even be operated manually. However, their use is usually limited to lightly traveled tracks (Health and Safety Executive, 2007). The excellent gauge restraint and increased lateral resistance for securing its geometry are among other technical advantages presented by steel sleeper. Additionally, damaged sleepers also have commercial value (Esveld, 2001), since the steel can be recycled several times and reused in the railway industry. In the search for further improving the characteristics of steel sleepers, the traditional orthogonal sleepers have been replaced by Y-steel-sleepers (Figure 2). The development of this new model provided a further reduction in weight of steel sleepers and gain of resistance against cross movements due to the amount of accumulated ballast in its central part as a consequence of its design similar to the letter Y (European Federation of Railway Trackwork Contractors, 2007; Tata Steel, 2014).

Fig. 2. Y-Steel-Sleeper

A significant disadvantage of steel sleepers is due to the difficulty to achieve a reasonable packing with ballast, requiring special care during the installation process and tamping (Kaewunruen, 2014). Other problems are corrosions, fatigue cracking in the fastening holes caused by moving trains, high electrical conductivity (that can lead to problems with track circuit signalling) and excessive noise also contribute to the inferior popularity of steel sleepers. However, the greatest restriction of the use of steel as a material for the production of sleepers is its excessive value (Manalo, 2011).

2.4 Plastic, polymer and composites

Material scarcity, as well as environmental concern, motivates researchers to develop new materials capable of satisfying the railway system requirements. Building a structure that is economically competitive and meets the needs of the industry is a major challenge of civil engineering. There is a constant search for a material that is durable, reasonably easy to produce and maintain, has attractive costs and meets the expected requests effectively (Manalo, 2011). A key concern in the railway industry is the replacement of damaged and deteriorated sleepers in existing tracks. The importance of the development of the polymer and composite sleepers is due to the capacity to design it to mimic the timber behaviour, which cannot be achieved with concrete and steel sleepers. A factor of extreme importance for the maintenance of timber tracks is consistent track stiffness. Moreover, polymer and composite sleepers require low to almost no maintenance, thus this improved lifecycle makes them a suitable alternative for areas that are harder to maintain such as tunnels, bridges, and turnouts. Another advantage is its sustainable approach, what makes them be notable in the face of the constant increase of concern over the existing environment in the current industry (Manalo, 2011; Griffin et al., 2014).

Many studies are given in the area of polymers and composites as material for the manufacture of sleepers. A composite material is manufactured from two or more distinct materials combined to achieve characteristics not found in those who compose (Griffin et al., 2014). There are several efforts towards improve the characteristics of the materials already used in the railway track engineering (wood, steel and concrete) as applied to the polymer by itself or composite polymers, using mainly fibres (Manalo, 2011). A fibre composites system characteristically consists of a lightweight polymer matrix with strong fibres inserted into it. The fibre reinforcement sustains the load due to its high strength and can be applied as reinforcement only in the longitudinal direction or longitudinal and transverse directions.

According to Manalo (2011), fibre composites could be perfectly suitable for the production of railway sleepers. These composite can be engineered based on the required structural applications and manufactured with almost the same dimensions and weight to that of hardwood timber. Additionally, fibre composites railway sleepers offer high strength, are light and present a longer lifecycle, reducing maintenance costs. Moreover, fibre composites are easy to handle, they can be drilled in situ for the connection of the fastener system and inserted under the track as timber sleepers. Another appeal of polymer and composites sleepers is the environmental solution. There are many efforts in developing polymers from recycled plastics. Since 1990 several U.S. companies and institutions have shown interest in the production of sleepers from recycled plastics. According to Lampo (2002), the recycled plastic material can help reduce emissions of greenhouse gas, save millions of trees, reduce chemical contamination due to the preservatives present in timber sleepers and also adding commercial value to a large amount of waste. Economically most fibre composite sleeper developments still have disadvantages compared to traditional sleeper materials due to higher initial costs (Griffin et al., 2014). Companies such as Carbonloc Pty Ltd. in Toowoomba, Australia, have devoted researchers for the shape optimization of polymer sleepers based on the load and support pattern, which can reduce considerably the volume of polymer needed while assure that it still achieves all the proprieties needed to cope with the railway requirements (Manalo, 2011; Silva et al., 2017).

3. Carbon footprint

The construction industry is one of the greatest consumers of raw material and energy, as well as a major generator of environmental pollution (Bilec et al., 2006; Kreso et al., 2016). Consequently, the choice of materials is a subject of ongoing debate. Considering railway engineering, several concerns arise when discussing manufacture, preservative treatment and disposal of damaged and deteriorated sleepers. The manufacturing process of railway sleeper can be associated with substantial environmental impacts. Resources required for the production of sleepers as energy and material are responsible for a large greenhouse gas emission (Crawford, 2009). Materials such as concrete and steel consume a significant amount of energy during production and could dispense respectively 10-200 times more carbon dioxide into the atmosphere than hardwood timber sleepers. Moreover, gases are also generated during the transportation and installation of sleepers and a great quantity of waste is resulted, mostly from the harvesting of timber (Crawford, 2009). However, during the service life, the decay of timber sleepers continues resulting in impacts to the environment. This is due to the fact that during their growth, trees lock in its structure carbon that is absorbed from the atmosphere and once timber has been cropped it progressively liberates carbon dioxide back to the environment. Then this emission is increasing even after the disposal of these sleepers after the end of its decomposition. As a comparison parameter, Crawford (2009) founds that emissions related to the service life of timber sleepers can be up to six times greater than the emissions associated with reinforced concrete sleepers. Another concern related to using and discarding of timber sleepers comes from the practice of chemically impregnating them with creosote to preserves it from biological deterioration (Griffin et al., 2014). Despite being widely used, toxic substances are present in these chemical preservatives, which do not easily decompose in nature and are volatiles (Bilec et al., 2006). So they are gradually released into the air during the life cycle of the sleeper and cause environmental pollution and present risks to human health. On the other hand, plastic sleeper, when made from recycled plastic, can be beneficial to the environment. Its production not only saves the use of other materials but also provides functionality to a considerable amount of waste as well as attaches commercial value to a material that would be discarded (Lampo, 2002). Though, the use of non-recycled plastic for manufacturing sleepers generates concerns mainly because of some plastics being a by-product of oil in addition to being non-biodegradable. Furthermore, the service life of the sleepers has a great impact on its sustainability since it determines the demand of material over the years, and also the amount of discarded units, which generates great impact especially on the use of waste land. The expected service lives of the different types of sleepers are listed on the Table 1.

4. Climate uncertainties

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014) summarized the trend of the climate change. The IPCC pointed out that warming of climate system is obvious and definite. The IPCC summarized that the temperature increased from 0.0045◦C per decade in the past 150 years to 0.074◦C per decade in the past 100 years, and 0.177◦C per decade in the past 25 years, which shows acceleration trend. As a result, atmosphere and ocean are warming, polar ice caps are melting and extreme events will be more likely and frequently to take place. Figure 3 shows similar trend through plotting the data from IPCC.

According to Figure 3, the occurrence of extreme cold weather will take place less due to global warming. At the same time, there is much risk of hot weather in the tails of the distribution and events of more extreme hot weather happen frequently. In this case, it can be inferred that more hot weather will bring much drier, and warmer winter also can be more humid. In addition, there is significant increase in the CO_2 concentrations in the atmosphere.

Table 1. Expected life cycle of different types of sleepers/crossties (Sadeghi and Barati, 2010; Manalo, 2011)

Material	Service life (years)
Timber	15-25
Concrete	50-70
Steel	20-30
Plastic/Polymer	50+
Composites	50+

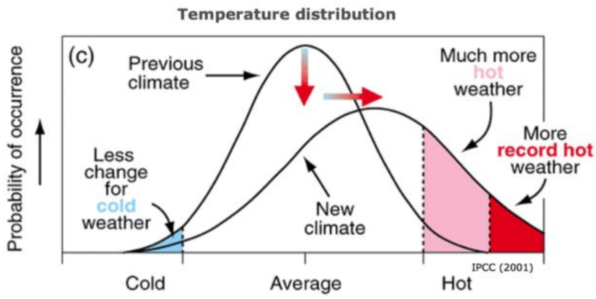

Fig. 3. Temperature change between previous and recent years (IPCC, 2014).

Table 3. Georisks of rail infrastructure due to sleeper materials

Probability Rank	Influence of sleepers/crossties	Impact Duration	Georisks	Climate Impact Group
High	• Embankment, rock cutting, earth cuttings and culverts are at risk of being instable, disregarding of any type of sleepers. • Steel sleepers tend to cause higher level of wheel-rail interaction and could cause significant ground-bourne vibration. In addition, ballast is vulnerable to washaway due to sleeper buoyancy behaviour. • Concrete, composite and timber sleepers can stabilise track better as well as reduce flow velocity in an event of flashflood, rainfall or water runoff.	>1 month	Geological stability	Increased rainfall
High	• Regarding the design of the track bed, the load distribution pattern at the sleeper/ballast interface is a parameter of critical importance since it is a major function of the sleeper smoothly distributes the loads imposed on it by rails to the subsequent layers. • The formation is often damaged by excessive moisture content especially when flooding occurs after rains. Concrete sleepers tend to cause formation failure quicker than other sleepers because they are often used in a heavier operation, resulting in a higher bearing pressure. Therefore, if formation is undermined by water, it is highly likely that such track will fail even though it looks perfect from the top view. • Reconstruction of track formation and foundation is required if damage occurs.	>1 month	Increased flooding and runoff	Sea level risk
High	• Dynamic and cyclic stresses are a major concern for the stability of the subgrade. Repeated traffic overloads are related with many subgrade problems, being the progressive shear failure and excessive plastic deformation some of the causes of formation failure most commonly found in railways around the world. Furthermore, the overstress can wear the superficial soil of the subgrade that combined with water form mud. More than the weakening of the soil, this mud under repeated loads can pumps into the ballast and damage the drainage of the track (using any type of sleepers). Fine-grained soils, as clays, are usually more susceptible to these failures modes. •Timber sleepers are often decayed with high moisture content, resulting in excessive track settlement later. • Steel sleepers can be oxidized at higher level.	> 1 month	Geotechnical failure, shear and plastic failures of subgrade and formation	Increased rainfall
High	Need to monitor the ground movement and the relationship with rainfall intensity. Settlement under heavy haul track is usually accelerating higher. However, deteriorated timber sleepers by moisture content can lose the vertical stiffness and yield excessive deformation and higher total settlement. Steel sleepers can corrode and can be electrolyzed by electrification and track circuit systems. Without appropriate track drainage, plastic and polymer sleepers can absorb water and perform poorly. Composite sleepers will suffer if water can leak into the gap between fasteners (e.g. bolts, screwspikes) and composite materials.	> 1 week	Differential track settlement	Increased rainfall
Medium to High	Sleepers have the major role of providing satisfactory lateral resistance to avoid lateral movements of rails. If the lateral forces overcome the lateral resistance of sleepers, rail buckling may occur. In fact, timber and steel sleepers perform poorly laterally under elevated temperature.	< 1 week	Track stability, track buckling or misalignment	Heat
Medium	• Steel, plastic and resin in composite sleepers become very brittle in very low temperature. These sleepers could be damaged by ice-stiffened tracks, resulting in excessive groundborne noise and vibration. • Low temperature influences unexpected failure modes of composite and plastic sleepers. • Freeze-thaw effects can cause concrete sleeper damage. • Ice-stiffening can cause ballast dilation, cracking subballast, cracking formation, and frozen rail joints. • Icing can also cause frozen rubber/under sleeper pad / under ballast mat.	< 1 week	Component damages, rapid deterioration	Cold snap

CO2 concentration also indicated the increase in trend from 280 parts per million in 1750 to 380 parts per million in 2005 (IPCC, 2014). The fifth assessment report showed an impact from recent climate-related extremes, such as heat waves, droughts, floods, cyclones and other extreme events. The IPCC also suggests that some frequency of combinations with extreme weather patterns will increase. For instance, the frequency of intensity of heavy rain in summer will increase, which means high temperature combined severe rain will appear together and as consequence the combined effect of these extreme weather will be more serious rather than effect of individual climate change on track superstructures and substructures.

5. Georisks

Railway track structure and substructure are expected to resist the static and dynamic loads that are generated by the passage of moving trains. Additionally, the cyclic characteristic of these loads has a great influence on the track long-term behaviour. Without appropriate design, construction, inspection and maintenance of track components, track stability can be undermined and the georisks can be increased (Osman et al., 2017), as shown in Fig 4.

Fig. 4. Track condition after a flash flood in 2016 (Courtesy: State Railway of Thailand). Concrete sleepers have ability to retain to certain extent the original alignment and geometry. However, it is important to note that replacing timber with concrete sleepers without improving ground condition can pose a significant georisk of formation failure and differential track settlements under various climate uncertainties such as high intensity rain, flooding and sea level rise.

A major challenge when it comes to investigating the behaviour of the track substructure arises from the variability of the substructure component's proprieties and their sensitivity and vulnerability to environmental conditions. Attributable to this characteristic, the analysis of dynamic and repeated loading becomes more demanding due to the non-linear stiffness presented by granular materials (Indraratna et al., 2011). Understand how the substructure components react when subjected to these loads, how the loads are transferred from the sleeper to the track substructure and how the interaction between the components of the superstructure and substructure occurs is extremely important to the design, efficient operation and security of railway roads exposed to extreme events. Table 3 illustrates georisks under climate uncertainties. It is in fact the outcome of risk analysis and reprofiling against the climate uncertainties and the influential factor of sleeper materials. Note that it has never been presented by other researchers or practitioners (Kaewunruen et al., 2016). The risk register table is derived from rigorous expert interview, and the risk reprofiling and ranking takes into account train-track interaction with various sleeper materials. The insight into the risks and consequences can help determine priority for track maintenance activities facing the climate uncertainties.

6. Conclusion

Despite the importance of the dynamic sleeper/ballast interaction to the whole stability of railway tracks, few studies are previously focused on this aspect. From the critical bibliographic review, it can be possible to observe the influence of the sleeper materials in the interaction between train and track on the substructure of the railway line. Load transition pattern, sleeper capacity to dampen dynamic loads and bear lateral movements are important aspects to the stability of the track structure and substructure. Lower stiffness materials such as polymers, composites, and timber offer better ballast packing so that the sleeper-ballast contact pattern becomes more uniform and less concentrated stresses (more uniform) are transferred to the ballast particles and formation. Then, they tend to diminish the imminence of geotechnical failure and also increasing the durability of the ballast layer in the extreme climatic events. Importantly, vibrations can be better absorbed by timbers and composites reducing ballast wear and risk of damage to surrounding structures and geotechnical assets due to ground-bourne vibrations. The lateral stability is also highly influenced by sleeper materials and topology. The mass of concrete sleepers can indeed mitigate various georisks in the events of heavy rainfall and runoff. Also, sleepers with unusual forms such as twin block concrete sleepers and Y-shape steel sleepers has some advantage when considerable lateral stability is required. The soffit surface of concrete sleepers is proven to have excellent resistance to lateral movements. However, the damping deficiency of concrete sleepers under dynamic loading actions must be mitigated by using rail pads or under sleeper pads. It can be noted that polymers and composite sleepers could bring enormous advantages to the railway industry since they might require less maintenance and have longer expected service life. Its properties could potentially reduce the effects of dynamic loads. However, polymers and steel sleepers tend to have lighter weight and their buoyancy could undermine track stability and increase georisks especially when flash flood occurs. Based on this rigorous risk analysis and ranking, track engineers should carefully plan and develop climate change adaptation plan that is suitable for the track structure and its components and meets the demand for appropriate level of track maintenance and inspections to minimize crisis and consequence due to climate uncertainties.

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